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WAVE POWER TRANSMISSION

(A BRIEF STATEMENT OF THE PHYSICAL PRINCIPLES INVOLVED)

By W. DINWOODIE

A PAPER READ BEFORE THE NORTH EAST COAST INSTITUTION OF ENGINEERS AND SHIPBUILDERS ON THE 27TH OCTOBER, 1922, AND REPRINTED BY ORDER OF THE COUNCIL.

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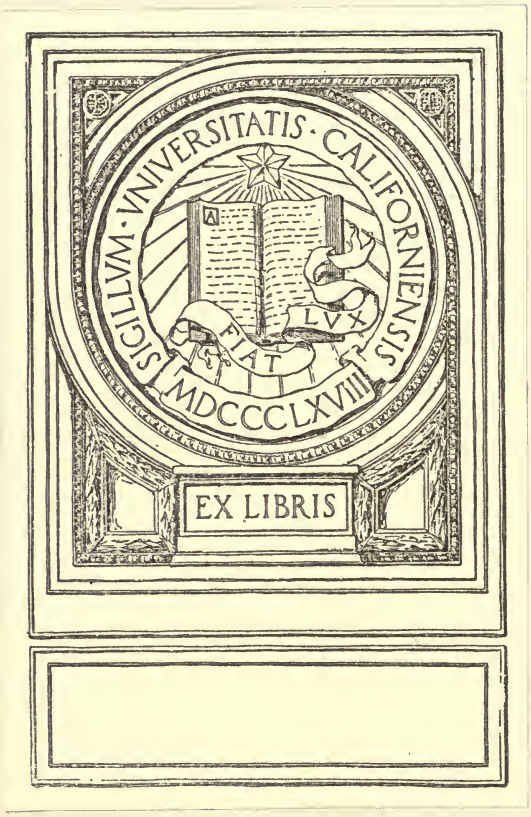
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WAVE POWER TRANSMISSION.

By W. DINWOODIE.

UNIV. OF CALIFORNIA

WAVE POWER TRANSMISSION.

(A Brief Statement of the Physical Principles Involved.)

By W. Dinwoodie.

[Read in Newcaste-on-Tyne on 27th October, 1922.]

The system of power transmission forming the subject of the following paper is the outcome of the invention of a Roumanian mathematician and engineer, Mr. G. Constantinesco, by whom the invention was announced shortly before the recent war. Financial backing was forthcoming through Mr. Walter Haddon, and an early result of their efforts was the now famous C.C. Interrupter Gear, for the control of machine gun fire through a sector swept out by the propeller of tractor type aircraft.

During the war development along commercial lines was of course much impeded, but since that time has been steadily progressing. The writer of this very incomplete description of the system is indebted to Mr. Haddon, and Messrs. W. H. Dorman, of Stafford, for kind permission to acquire the necessary information, to take photographs of plant, and other assistance.

In endeavouring to prepare a paper on the subject of Wave Power Transmission, one immediately realizes that the matter dealt with must come under two main headings, first a discussion of the theory and second a description of the practical machines and appliances which are an outcome of these considerations. While no doubt a description of the design and operation of the plant would be of greater interest to engineers, nevertheless, it is obvious that a full appreciation of the points met with in the description of the developments of the system cannot be attained without a knowledge of the principles underlying them.

Since, with the exception of alternating current electricity, the physical phenomena associated with the system differ so much from other means of transmitting power, and, in addition, because a knowledge of such phenomena adds greatly to the interest of the subject, the writer has ventured to preface his remarks by a consideration of wave motion in so far as that subject bears on the ground to be covered by the paper. In order to understand the principles of the system a knowledge of the fundamental properties of wave motion is very desirable, since under

given circumstances the waves employed undergo the same modifications as similar waves in other media. Those desirous of studying the matter more fully, and of acquiring in a most interesting form further knowledge of the subject of waves could hardly do better than read the series of lectures on "Vibrations, Waves and Resonance" delivered by Dr. Erskine-Murray before the Royal Society of Arts.

When a body executes a motion at regularly recurring intervals of time, the motion is said to be periodic. When this motion is, in addition, continually and periodically reversed in direction, it is said to be vibratory. A wave is the transmission of such a motion through a medium. Consider a straight line composed of particles of air connecting the source of a continuous note with one's ear, and assume that the sound is produced by the vibration of a plane diaphragm. On the outward stroke of the diaphragm the particles near it would be com pressed, because of the inertia (or tendency to stay still) of the particles more remote, while the compression is rendered possible by reason of the elasticity of the air.

While this compression is taking place, however, the elasticity of the air causes an expansion outwards giving rise in the same way to a zone of compression slightly more remote. On the return of the diaphragm the air in contact with it expands back again until the mean position is reached. The continuation of the motion of the diaphragm beyond this point (again by reason of the inertia of the air) creates a region of reduced pressure into which air expands from more remote positions. Thus the vibrations impressed on the particles of air adjacent to the diaphragm give rise to similar vibrations in other more remote particles by reason of the elasticity, while, owing to the inertia of the air, these vibrations are each slightly displaced in time from the original. The continuation of the motion of the diaphragm results in all the particles of air between the latter and the ear performing a similar vibration with the effect of producing waves of compression and rarifaction in the air, those particles adjacent to the drum of the ear imparting their motion thereto and giving rise to the sensation of sound.

In this form of wave motion, the movement of the particles is to and fro along an axis lying in the same direction as that of the wave's progression. Such waves are called longitudinal waves, as opposed to those, such as ocean waves, where the motion of the particles of the medium is on an axis at right angles to the direction of motion of the wave, shown by a cork floating on the surface of the water. The latter are known as transverse waves, and with ripples or capillary waves have many characteristic associated phenomena which do not enter into the present consideration of longitudinal waves.

The fact that one can hear many sounds from diverse sources simultaneously and distinguish between them, proves that many waves may be propagated simultaneously through the same part of the same medium without becoming distorted. The effect, in such a case, on the particles of the medium is a displacement corresponding to the algebraic

sum of all the individual displacements due to the several waves. The phenomena is a characteristic of all such waves.

The reflection of waves is also an everyday phenomenon of accoustics, and is equally associated with waves in other media. Reflection, indeed, plays an important part in the wave system of power transmission as will be seen later when the system as practically developed is described.

In speaking of the properties of vibrations and waves the unit of time in which the motion of any particle is completed is called the period, and the number of such periods or cycles per second the frequency. Referring back to the sound analogy, when the diaphragm has passed its outer extreme position it is shown that a zone of high pressure is progressing through the medium, as a result of the vibrations imparted to successive particles of air each differing slightly in phase (*i.e.*, a time relationship) from that of the adjacent particles. In other words, the vibrations of particles successively more remote from the source, pass (in the same direction) a given point in their paths at slightly later instants.

The distance traversed by this first region of compression when the diaphragm again reaches its outer extreme is known as the wave-length and in waves of the type to be considered in this Paper this distance is almost independent of all factors except the elasticity and the density of the medium in question.

Newton's expression for the velocity of a longitudinal wave in a homogeneous medium is—

$$V = \sqrt{\frac{E}{D}}$$

Where V = Velocity
E = Modulus of Elasticity
D = Density, or mass of unit volume,

and this expression is seen to be independent of the wave-length or frequency.

It follows that the product of the wave-length and the frequency equals the velocity in any given medium.

The choice of medium in the application of this theory to practical requirements is of course unlimited. A gas or mixture of gases might be used. Liquids such as oils and water are the media at present used in development of the system, while the transmission of impulses along an enclosed steel wire was an early adaption by the inventor, to meet the requirements of a synchronized trigger release gear for machine guns. Thus, where in the course of this Paper water is specifically referred to as the medium, it must be understood that analogous effects might have been produced in any elastic media.

Of course, one must realize at the outset that the assumption generally made in hydraulics that water is incompressible is only relatively true. By comparison with gases, this is practically correct, but compared with metals it is very far from the truth. The Modulus of Elasticity of water is approximately 250,000 lb./sq. in., while for wrought iron it is about 27,000,000 lb./sq. in. Thus the ratio is of the order of 1 : 100.

In the following paragraphs, therefore, where water columns enclosed in steel pipes are considered, the expansion of the pipe is for present purposes a negligible factor of the volumetric change due to pressure.

Consider a pipe line of great length and, say, 1 inch bore, closed at one end, completely filled with water, while a fluid-tight plunger works in the cylinder formed by its other end. Suppose this plunger to be connected to a crank of small throw by a connecting rod of long length in proportion to this throw. Then, if the crank be rotated at uniform angular velocity, the plunger will reciprocate in the cylinder with very nearly Simple Harmonic Motion. The name Simple Harmonic Motion is due to the fact that most of the vibrations met with in the study of sound may be shown to be compositions of few or several of such vibrations, which have certain simple and definite mathematical characteristics.

Let OP represent the crank rotating about O, and D the plunger moving in the path aa'. Then if 1, 2, 3, 4, . . . 8, are points dividing the semi-circumference into eight equal arcs, the point P will pass

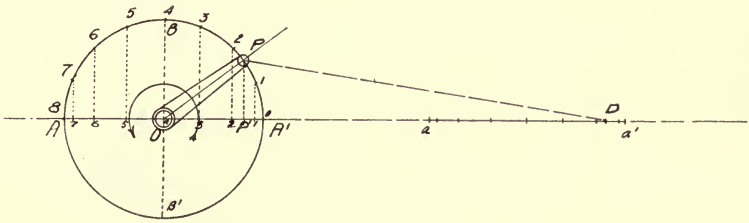
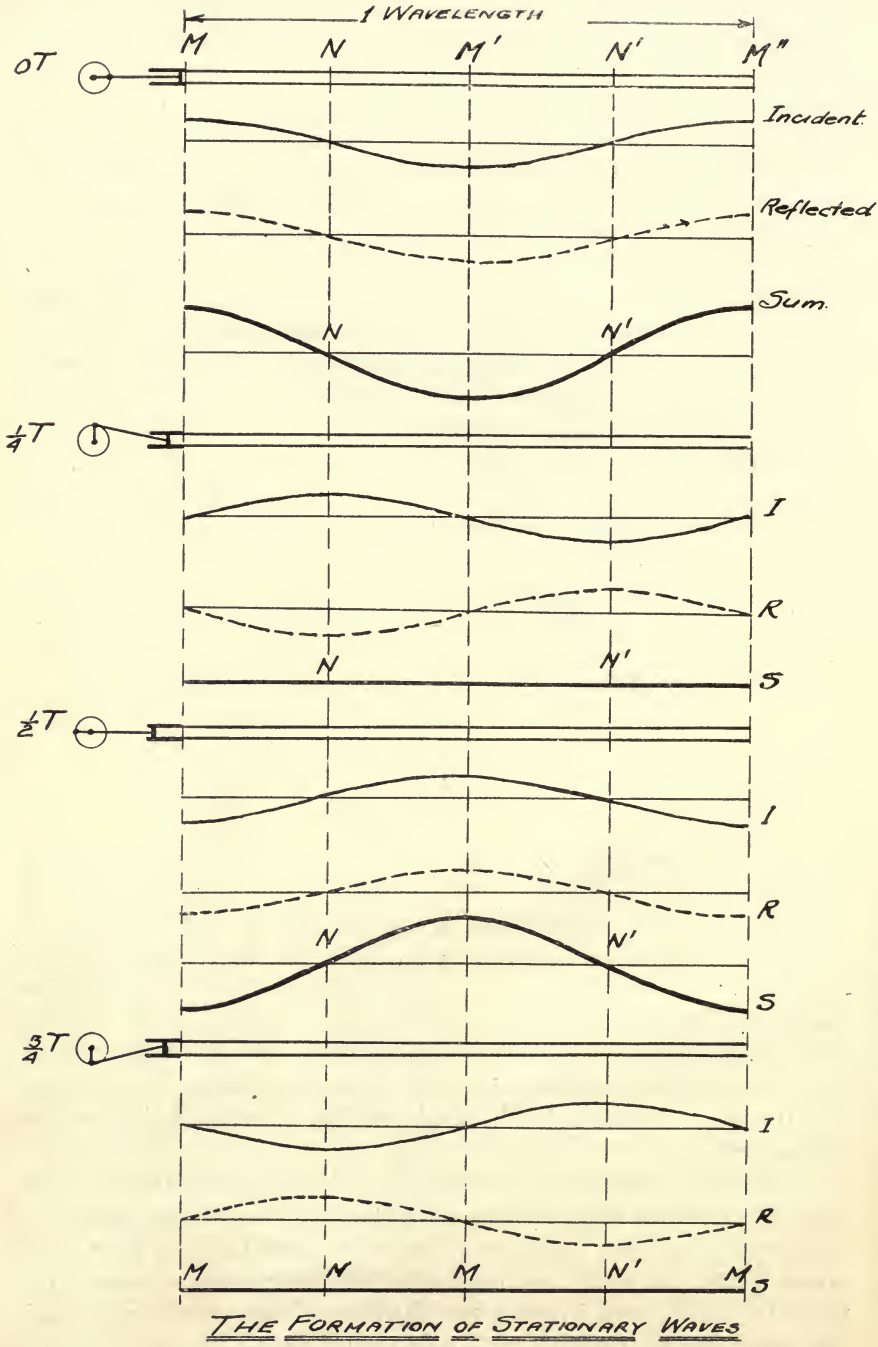


FIGURE 1

through them at equal intervals of time. The plunger will similarly move through the distance A'A in this time, but it is seen that its velocity will not be uniform but a maximum at O, and decreasing to zero at A, prior to increasing to a maximum in the opposite direction on the second half revolution of the crank OP. If O be the mean position, it is seen that at any instant represented by OP the displacement of the plunger is given by the projection OP' of OP on the line AA', or expressed mathematically, the displacement from O will always be OP cos α, where α is the angle included (anti-clockwise) between OA and OP.

If the time or angular displacement of the crank be plotted as a base and the displacement plotted as ordinates, positive to the right of O and vice versa, then the extremities of these ordinates will lie on a cosine curve (or very approximately so, depending on the ratio OP : PD). The curve is called the Harmonic Curve when used to show the relationship between the displacement of a particle executing Simple Harmonic Motion and the time; while later it will be seen that other functions of this motion will also bear similar relations to time, etc.


1 WAVELENGTH
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N'
M
S
THE FORMATION OF STATIONARY WAVES

FIGURE 2.

Returning to the closed water-filled pipe, suppose the stroke of the plunger referred to is 1 inch, and the pipe 300 feet long, then the half displacement of the plunger (*i.e.*, from mean position) will be ·375 cubic inches (approximately) and the volume of the water in the pipe-line 2,700 cubic inches. If the crank were rotated very slowly this displacement would give rise to a pressure rise of about 40 lb./sq. in. In this case the effect of the inertia of the water is reduced to a minimum. Were the compression carried out infinitely slowly the inertia effect would be zero, while as the speed of rotation of the crank increases, the inertia of the water acts to an increasing extent as a buffer against which the layers of water near the piston are compressed, until with a period of 1/40th second a displacement of the order mentioned acting into such a pipe line gives rise to a compression zone whose pressure is of the order 600 lb./sq. in. This figure is given to illustrate the effect of inertia, and of course is not absolute, since many other factors influence the result.

The cycle of pressure change is, in this case, analogous to that obtaining with the vibrating diaphragm considered earlier. Here the velocity is found to be approximately 4,800 ft. per second, and thus if the frequency is, say, 40 cycles per second (to name a frequency often adopted in percussive tools), then in 4,800 ft. of medium there will be 40 zones of compression, the distance between each crest being $\frac{4800}{40}$ or 120 ft., which is, for this frequency, the wave-length.

Now consider for simplicity a pipe of this length closed at one end and filled with water and a plunger oscillating in a cylinder formed at the other end, with a frequency of 40 cycles per second. Waves of compression and expansion will be propagated through the water column, and will be reflected back from the stop. (For the first consideration of the effects of this reflection it will be assumed that the reflected waves, on reaching the generator after reflection, have no further effect on the system, while the diagram is similarly prepared only to illustrate the formation of Stationary Waves.)

In Fig. 2 the top set of curves represents the state when a zone of high pressure is leaving the plunger face. The last propagated high-pressure zone will be at the stop, and the penultimate will have been reflected back to the plunger. The incident wave is shown in a full line, and the reflected wave in a broken line, the two curves being separated for clearness. The resultant effect upon the particles of the medium is the algebraic sum of the individual effects, this condition being shown by the thickened curve below the incident and reflected waves.

The following three curves show the state of affairs $\frac{1}{4}$ cycle later. Each wave has progress by $\frac{1}{4}$ wave-length, and the sum at all points along the wave-length is seen to be zero.

The third set of curves illustrate the state of affairs $\frac{1}{4}$ cycle later, *i.e.*, after half a revolution, when the amplitudes are again additive. At $\frac{3}{4}$ revolution the two superimposed waves cancel each other and the

displacement is zero all along the water column, while the position after one complete cycle is a repetition of the conditions represented in the first set of curves.

It is seen that the points on the water column at N and N′ experience no pressure change during the complete cycle, while between these points the pressure alternates between limits which reach a maximum of twice the amplitude of the incident wave at the points on the lines MM. The condition is illustrated in Fig. 2A, where the full lines show

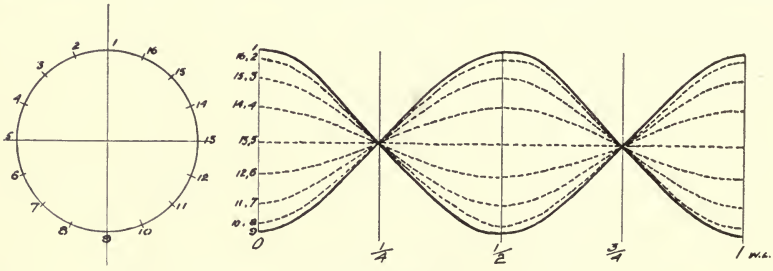


FIGURE 2A.

the amplitude of the pressure change at points along the column, while the broken lines illustrate the state of the water column at various points in the cycle. This condition, when the troughs and crests of the wave do not progress, is called a Stationary Wave. In the above circumstances, however, the effect of the continued reflection of waves has been disregarded.

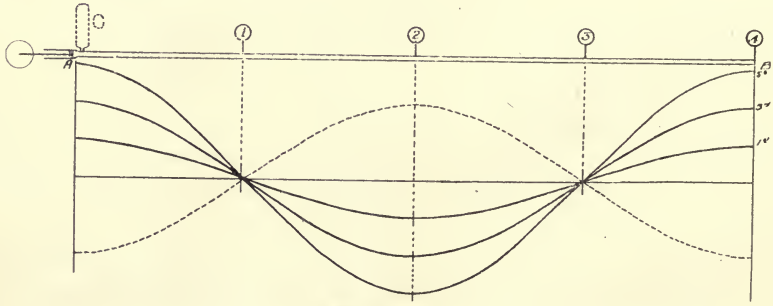


FIGURE 3.

Fig. 3 is another diagram of such a pipe line, and it will be observed that when the third high-pressure zone is leaving the plunger face, the first is arriving at that point after reflection from the stop B. A wave of twice the original amplitude is thus propagated on this cycle and the subsequent one. On the next cycle, however, the reflected wave will be of twice the original amplitude, and the fifth cycle will thus propagate a wave whose maximum pressure will be thrice that of the original wave. This process will be repeated at every alternate cycle and the maximum pressure would, in much less than a second, exceed the limit imposed by the strength of the pipe, and a burst would result.

Now the above would represent the state of affairs when the machines operated by a wave generator where either shut down or were absorbing less than the total available generator output, a condition which obtains at all times except perhaps when an attempt to overload the generator is made. It is, of course, essential that this prohibitive limitation should be overcome, and this is achieved by placing in communication with the pipe line near the generator cylinder an enclosed volume of water shown at C. This vessel is known as a "capacity" and is analogous in its action to a condenser in alternating-current electricity or a spring in mechanics. The inward stroke of the plunger causes an inflow to the capacity in addition to the propagation of a pressure wave along the column. This inflow causes a rise in pressure in the capacity and a corresponding storage of energy. As the revolution of the crank proceeds and the pressure at the plunger face falls, the capacity, by reason of the elasticity of the water and the pressure difference, returns this energy to the system in expanding once more to normal pressure. This inflow to the capacity at instants of high pressure in the neighbourhood of the plunger, and the return of the energy thus stored on the reverse stroke of the generator is, by suitable design, made to correspond to the total generator output when the stationary wave of the desired amplitude has been produced in the closed pipe line. The output of the generator under these circumstances is theoretically zero; actually, of course, energy is supplied to maintain the stationary wave, and to compensate for the energy dissipated by internal and inter-molecular friction, etc.

This arrangement, the description of whose operation is necessarily incomplete since its action if considered in detail is dependent on many other factors, satisfactorily provides for the independent stopping and starting of machines operated from a pipe line. The next point arising is the facility with which machines may be tapped in on such a pipe line.

Consider a pipe line in communication with which are four wave-power tools, fitted with stop cocks, tapped in as shown in Fig. 3. It will be remembered that in the consideration of the stationary wave it was shown that the particles at $\frac{1}{4}$ and $\frac{3}{4}$ wave-length were permanently at the mean pressure of the system, while those at multiples of half wave-lengths experienced a maximum pressure change of twice that of the original wave. As might be anticipated, machines tapped in at points 2 and 4 will be self starting, and will be stable in running, while those at 2 and 3 will not start when placed in communication with the stationary wave. If, however, the motor at 4 is in operation, then a progressive wave will be superimposed on the stationary wave, and since the nodes and antinodes of such a wave will travel along the column, at no point therein will the pressure change be permanently zero, and the machines at 1 and 3 will start. Were (2) the only machine in operation, then machines between it and the generator would be self starting, while beyond (2) the stationary wave alone would persist.

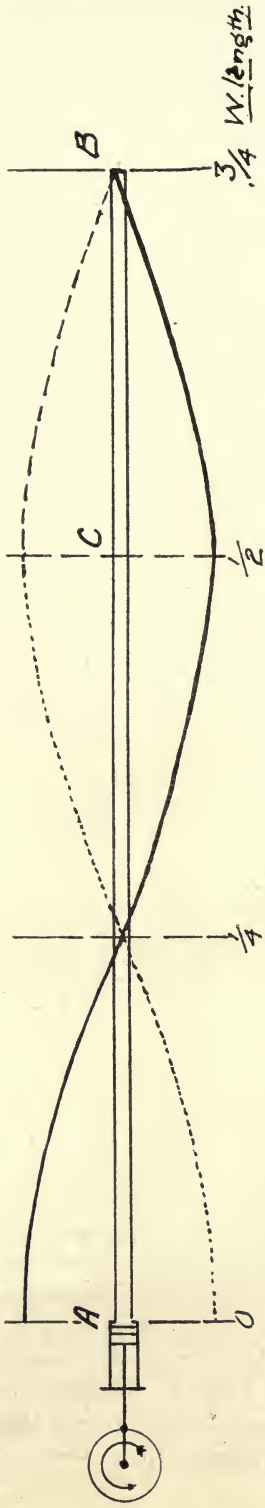


FIGURE 4.

The conclusion, therefore, is that to be stable in running and self starting, machines should be placed in communication with a transmission column at points which are multiples of half wave-lengths. Similarly in order to enable a stationary wave to be set up and maintained in the transmission column, the length should be similarly governed.

The question of the limits between which such dimensions must be observed next arises, and the information is forthcoming on consideration of the effects produced by pipe lines of lengths other than multiples of half wave-lengths. Instead of a generator running at 40 cycles per second on a pipe line of 120 ft. (one wave-length) suppose that the line is reduced to 110 ft. It is seen that a stationary wave cannot normally be produced with the frequency unaltered. The result is that the generator takes the easier course, as it were, and the speed tends to adjust itself so that the length of the transmission column is in effect a multiple of half wave-lengths. In the case cited above, the frequency (*i.e.*, the generator speed) would tend to become that for which 110 ft. represents the wave-length, and since the velocity must remain constant, this frequency would be 4,800/110 or 43·7 cycles per second, an increase of speed of about 9 per cent.

In order that the frequency shall remain constant the speed of the generator is governed within a variation not likely to exceed 5 per cent., and, in the effort to resist the tendency to speed adjustment, much power will be wasted; but had the line been composed of 470 ft. in lieu of four wave-lengths (480 ft.) the adjusted wave-length would be 117·5 ft. Thus the same linear error in the pipe line would result in a speed increment of only 2 per cent. The effect of such difference from multiples of half wave-lengths is thus proportional to the ratio between the difference and the total length of the pipe line, and it is found that beyond 300 ft. (with the frequency 40) the governing of the generator permits of this adjustment without loss of power whatever the length of the pipe line.

With a permissible speed variation of 5 per cent., therefore, one may run with a line of within 5 ft. on one wave-length, this latitude being increased in direct proportion to the number of wave-lengths, while the maximum possible deviation from a half wave-length (*i.e.*, 30 ft.) is permissible at lengths of 360 ft. and over.

It is important to note the effect when a pipe line much outside the limit allowable is used, say one of $\frac{3}{4}$ in lieu of a wave-length. Here, of course, the generator cannot possibly adjust its speed by the requisite amount. Such a column is shown diagrammatically in Fig. 4. If T seconds be the period of the oscillating plunger and at O seconds a zone of high pressure is assumed to be leaving the plunger face (with the capacity pressure at its maximum), then at T seconds this zone will have reached the stop B and will have been reflected to C. After 1·5 T seconds this reflected zone will have reached the plunger face, where normally the pressure would have been a minimum. The arrival of

the reflected wave will have had the effect of maintaining the pressure at the plunger face at its mean value, thus preventing the outflow from the capacity. Subsequent cycles will repeat this process, while the capacity will, in effect, be cut out of the circuit with the speedy result of a burst becoming possible.

This concludes a brief description of those physical principles which underly the laying out of a Wave Transmission system. It now remains to discuss the operation of suitable "receivers" or means of converting the energy of the arriving waves into useful work.

In order that a machine shall be capable of operating thus it must be "resonant" to the waves supplying energy to it, or in other words, capable of utilizing at all instants the effort of the supply, in whatever sense or direction it may tend to act. The action of a pendulum is analogous. If a pendulum be struck lightly in one direction at intervals which correspond to the natural period of vibration, it is able to absorb the energy imparted and by its absorption do "useful work," *i.e.*, develop a correspondingly greater amplitude. If the impulses were caused to arrive much more rapidly and at irregular intervals of time, the energy dissipated would be much more, while the amplitude would be negligible. This principle is often applied in the removal of the garden roller from a rut in which it has come to rest.

Wave-power machines may be classified under headings as follows:—

1. *Reciprocating*—(*a*) Continuous Wave—where the generating plunger moves with maintained Simple Harmonic Motion.

(*b*) Impulsive Wave—a type in which a single harmonic motion is transmitted in wave form at regular intervals, greater than the period of the motion itself.

2. *Rotary*.—Under this heading will come types of Synchronous and Asynchronous motors, monophase and polyphase, in which direction research is at present proceeding.

Of course, many other classifications might be made, but these will suffice for the brief descriptions possible in a paper of desirable length.

In the following paragraphs an installation transmitting power by continuous waves will be described. Of such applications most attention has been paid to the development of a rock drill of the hammer type, and this form of reciprocating tool will be dealt with as a representative type.

In order to propagate waves of harmonic form in an enclosed water column, a surface in contact with the column is given simple harmonic motion. For obvious practical considerations the requisite displacement is distributed over two cylinders in which plungers are reciprocated by means of two cranks set at 180 degrees. This part of the generator may be visualized as resembling a horizontally opposed high-speed plunger pump, with each cylinder communicating with a large water vessel (the capacity) from which the transmission line is lead away.

The whole system from the generator plunger to the tool plunger, is to be filled with water, air being eliminated. To accomplish this,

and the lubrication of the generator bearings, a transverse shaft is driven by a worm on the front end of the crankshaft, engaging with a worm wheel, and upon this two cams are formed, also at 180 degrees. Two plunger pumps working against return springs are operated by these cams, through suitable tappets, the left hand pump forcing oil to the bearings and the other supplying water to the system, and providing for the maintenance of the volume. Chiefly in order to facilitate the elimination of air, and to maintain the stresses in one direction, a minimum pressure of 100 lb./sq. in. is maintained in the pipe line. The water pump must therefore be capable of a delivery when the capacity pressure falls below this, and must be so arranged that the delivery may be variable to correspond with the varying deficiency due to the water flush used with the drill and unavoidable leakage.

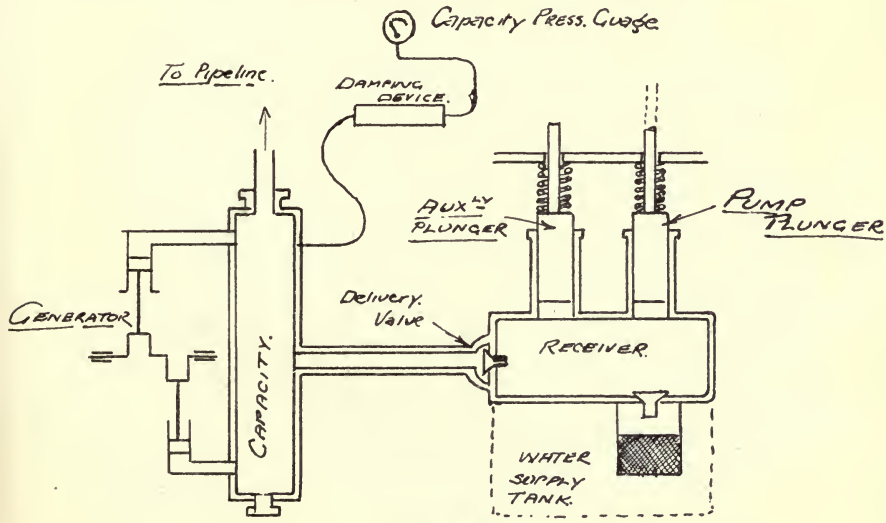


FIGURE 5.

These conditions are satisfied by the addition of an auxiliary plunger of similar displacement, working against a spring which is set to lift at a pressure of 100 lb./sq. in. This is placed in communication with the delivery chamber of the water pump, as shown in Fig. 5. This illustrates (of course, diagrammatically) the water system of the generator. On the upward stroke of the pump plunger, water is drawn in from the sump through the inlet valve. On the downward stroke, in the event of the minimum pipe line pressure being equal to, or more than 100 lb./sq. in. the delivery valve does not open, but the auxiliary plunger is raised against its spring. The whole of the displacement of the plunger is thus stored at a pressure of 100 lb./sq. in. or a little in excess of this. As long as the auxiliary plunger is lifted from its seat (*i.e.*, during most of the stroke) the pressure in the delivery chamber is 100 lb./sq. in., while the delivery valve to the capacity is a light disc valve operated by pressure difference, and will admit water to the

system at moments when the pressure therein falls below the minimum desired.

To facilitate the charging of the system and the elimination of air, air release valves are fitted at the highest point of the water circuit, over the generating cylinders and, if necessary at convenient points in the pipe line (similar air release valves are found in the water chambers of the rock drill). The transmission line is connected to the capacity through a stop cock, by means of which the pipe line is disconnected from the generator while the latter is attaining full speed, or while it is being shut down. One necessity for this is due to the

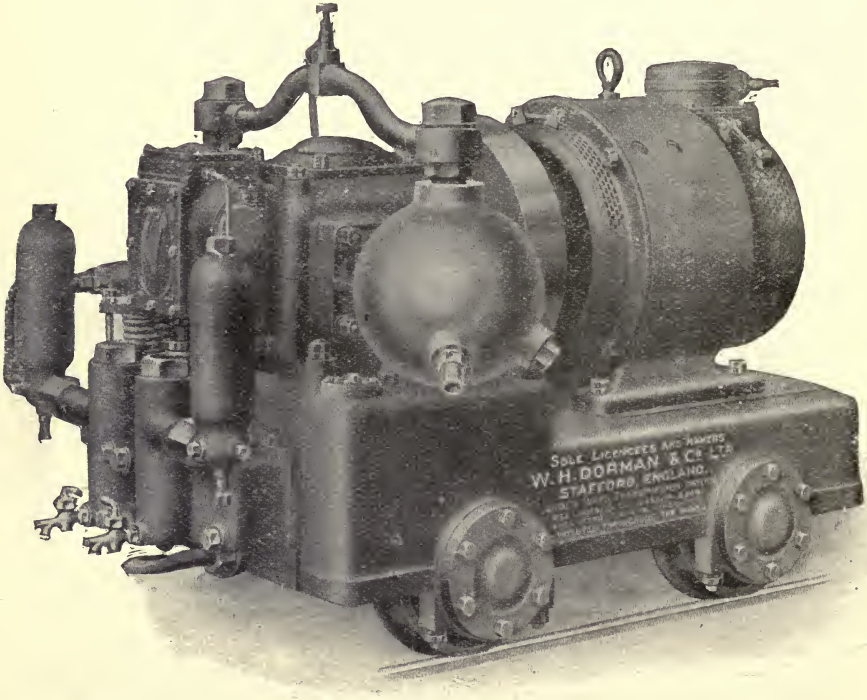


FIGURE 5A.

fact that a pipe line of $\frac{1}{2}$ wave-length, say, will, at half generator speed (therefore half frequency), behave as a quarter wave-length. Since the generator must pass slowly through all speeds while starting up and stopping, it follows that at some speed the effect of a quarter wave-length would be produced were the pipe permanently in communication with the generator. A very few cycles near this frequency would, it has been shown, result in a burst due to the cutting out of the capacity.

The above are the principal features of the generator sectional and other views of which are shown in the appended illustrations.

The pipe line of a wave-transmission installation may be built up of any piping of suitable bore whose walls are capable of withstanding the

pressures adopted. As in the case of electrical transmission, the cross section of the pipe required depends on the power to be transmitted and vice versa. The relationship is (approximately) that the power a pipe of given bore is able to transmit varies directly as the cross-

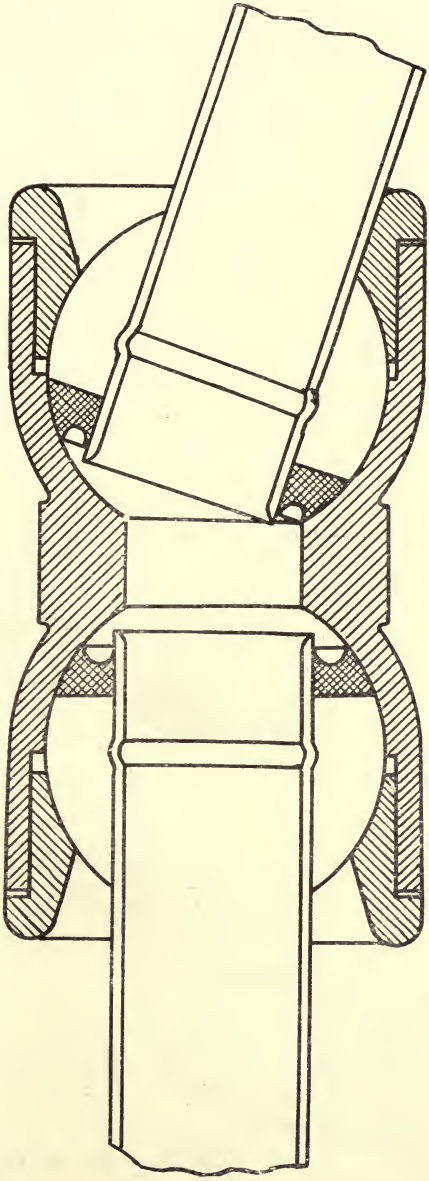
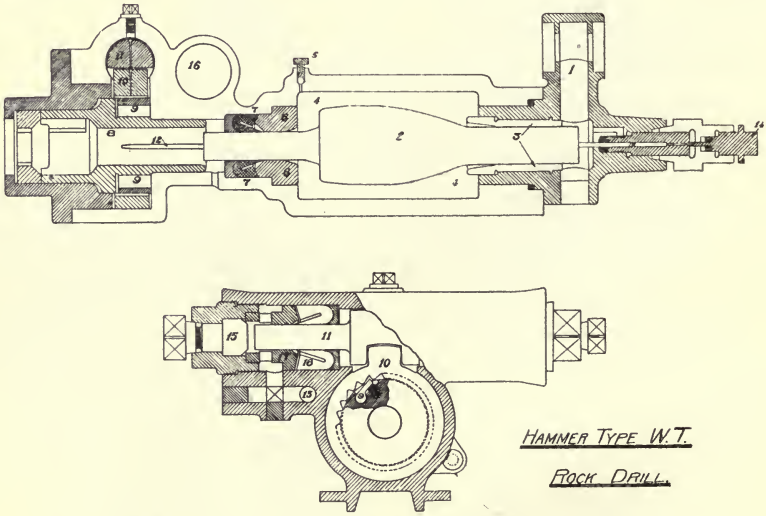


FIGURE 6.

sectional area, or as the square of the diameter. An idea of the numerical values found to obtain is given by the following case. With a pipe of one inch bore, a frequency of 40 cycles per second and a pressure range of 1,500 lb./sq. in., it is possible to transmit up to 15 h.p. without loss of efficiency.

Where flexibility of the pipe line is desirable (*i.e.*, near the generator and the tool, where the tool is of a portable nature) a piping such as that illustrated in Fig. 6 is employed. At the ends of two lengths of solid-drawn steel tubing, flatted ball pieces are pressed on and secured. These fit into spherically seated recesses machined in a union piece, and are secured by a suitably shaped retaining nut. A special packing ring is pressed over the projection of the tube beyond the flatted ball piece as shown. The piping does not tend to straighten out under pressure, while a length tested to destruction at the National Physical Laboratory which yielded at 9·2 tons per square inch, demonstrated that the walls of the tube give way before the joint or the packing.



1. WAVE INLET.
2. HAMMER.
3. MEAN PRES. LEAK BUSH.
4. CAPACITY.
5. AIR RELEASE VALVE.
6. STOP BUSH.
7. HAMMER PACKING.
8. CHUCK.
9. PAWLS.
10. RATCHET RING.
11. ROTATION PLUNGER.
12. WATER TUBE.
13. INLET TO ROTATION.
14. WATER FLUSH CONTROL.
15. STOP (R.P.).
16. ROTATION CAPACITY.
17. ,, M.P. LEAK BUSH.
18. ,, PACKING.

FIGURE 7.

This form of tubing is particularly suited for use with wave-transmission installations, since high alternating or mean pressures do not tend to straighten it out, as they would a hose, while sections may be added or removed as desired.

The rock drill which is to be dealt with as representative of reciprocating machines in general, has, of course, much in its design peculiar to the very severe duty it is called upon to perform. The scope of this paper, however, does not permit of a discussion of such points. The tool, of which a general view is shown in Fig. 7, consists of four main elements, a reciprocating hammer, a means of holding the

drill steel, a means of rotating this steel in a manner independent of the hammer blow, and a means of supplying a jet of water at mean pressure to the hollow drill steel. The hammer (*vide* Fig. 7) is a double-ended plunger rendered massive in the central section, the foremost or striking plunger being of smaller diameter than the rear. This is held, as shown, in two bushes (a packing being provided at the front end) and surrounded by a suitable water space. The rear of this hammer enters a space with which the wave may be placed in communication, by means of a suitable cock. On the arrival of the impulse this hammer is driven forward into the capacity and strikes the drill steel, while by reason of the difference in diameter of the rear and front plungers, the water in this capacity is compressed. As the pressure falls in the pipe line, this energy stored in the capacity acts on the differential area and forces the hammer back to its former position in readiness to receive the subsequent impulse. The water surrounding the hammer body acts as a fluid spring, absorbing energy in one half cycle which it returns to the system in causing the return stroke of the hammer. This cycle is repeated at the frequency of the system; in the case considered this results in 2,400 blows per minute.

The rotation of the drill steel must be carried out in such a way that there is no force tending to produce rotation during the striking movement of the hammer. This is carried out by the mechanism shown in Fig. 7.

The drill steel is provided with two lugs on opposite sides of the shank, this fitting loosely into a member known as the chuck, in such a manner that the rear of the steel abuts the striking face of the hammer. Pawls are arranged on the outside of this chuck, which is embraced by a ratchet ring having a lug formed on it as shown. This lug is received in the slotted barrel of a double-ended plunger, one end of which is placed in communication with the incident waves by means of a channel to the inlet chamber, while the other works into an enclosed volume of water (*i.e.*, a capacity). The pawls are set so that the incident wave causes the plunger to rotate the ratchet ring through a small arc without rotating the chuck. This movement must, of course, sychronize with the blow of the hammer, and gives rise to an increase of pressure in the capacity, which, during the following half cycle, causes the return of the plunger, and, by the engagement of the pawls with the ratchet ring, the rotation of the chuck and drill steel. This rotation, it is seen, must synchronize with the return stroke of the hammer.

The water flush is carried out by means of a water tube passing centrally through the drilled hammer from the rear of the inlet piece. A small passage to the rear of this tube is provided, such that in passing, the pressure alternations are almost damped out, and a needle valve, operated by the drill runner, is fitted by which the volume of the flush is controlled.

This concludes a very brief description of the Drill, which, together with the description of other plant, the writer hopes to augment at the time of the delivery of this Paper. A complete description on this side of the subject would occupy space equivalent to a paper of unwieldy size, and thus it would appear better to allow these points to be dealt with verbally when time need not be wasted on description of machine parts and general arrangements, which are readily apparent from the illustrations it is hoped to provide.

DISCUSSION.

Mr. Thomso

THE CHAIRMAN, Mr. Harold Thomson, *Vice-President*, said that it would be agreed that Mr. Dinwoodie had delivered a very interesting lecture, and he could only hope the members present had all followed the lecture as clearly as Mr. Dinwoodie had delivered it. Personally he did not feel quite capable of criticizing some of Mr. Dinwoodie's earlier remarks. Wave transmission was a very difficult subject, whether applied to light, sound or fluids; but he had no doubt there would be some members present who would like to ask certain questions. He was not quite clear about one or two small points himself. For instance, what happened if air got into the system? Mr. Dinwoodie had on his machine two air vessels, which, presumably, contained air; and if one could afford to have air vessels here did it make very much difference if air was present in other parts of the system? Again, if this system was adopted in shipyards, for working drills, etc., would it be necessary to study the theory of wave transmission before being able to lay out the piping system? He rather gathered that under certain conditions matters corrected themselves, but he was not quite sure on that point. If engineers in shipyards and works had to make calculations, regarding the positions of nodes and so on before they added additional tools to a system he wished them luck, but was rather glad he had not to do it himself as the matter seemed rather complicated.

In regard to variations in speed, would it be impossible to drive a machine of that kind with a constant speed in the motor? He rather gathered that the machine slowed itself down, and there might be some difficulty if they were using a machine with alternating current motors. With regard to rock drills, was it necessary to calculate the system of pipes so that these were in correct proportion to the wave lengths? In the event of the wave transmission system being developed, could portable hose of a rubber character be used? Would the expansion of the rubber pipe have a detrimental effect on the wave system? The Author said that the maximum pressure was 1,600 lb. to the square inch. Did that mean that the distribution pipes had to stand that pressure? If so, it might present difficulties in some classes of work.

Mr. Dinwoodie had explained that the firm had not yet made a complete study in order to apply the system to riveting and caulking tools and had really concentrated on rock drills with which they had had very satisfactory results, and the rock drill was now very efficient and he (Mr. Thomson) wished them every success in developing it further. He hoped some of those present who were enthusiasts on the subject of pneumatic rock drills would promptly tackle Mr. Dinwoodie and explain to him how much better the pneumatic tools could do the same kind of work, and ask the Author any questions which they might feel inclined to do.

Mr. Thomson

The Chairman asked, later, whether it was possible to tack an extra tool on to the system at a moment's notice.

Mr. Wilson

MR. R. W. WILSON asked what length of stroke the piston would make when it struck a blow.

Mr. Myles

MR. DAVID MYLES, *Fellow*, said, in connexion with the statement that a wave at sea was not a forward movement of the particles of water, that those who had been down at Tynemouth during a north-easterly gale must have been quite convinced that the water did move forward; but it had to be remembered that the conditions there were quite different from those obtained in deep water. At sea, where there was depth of water in proportion to the wave, it would be found that there was no forward movement of the water, and it was only when the wave came into shallow water that the particles of water moved forward. He had met men of considerable experience who did not agree with this and mentioned the effect of a wave striking the side of a ship, but they overlooked the fact that the ship obstructed the free movement of the wave and so caused the water to come on board.

If the branch pipe for driving any of the machines was taken off from the main pipe, the action of the water in the main pipe would set up another wave motion in the branch pipe. That, it seemed to Mr. Myles, would have a very disturbing effect on the wave action in the main pipe. Perhaps Mr. Dinwoodie would state whether that was so or not, and if it was so, what the effect of it was. He thought the Chairman had mentioned that so far there has not been much experience with ordinary chipping or caulking or riveting hammers, but it would be interesting to know if there had been any trials with those tools and what the results were—whether they appeared to be encouraging or otherwise. It seemed to him that wave motion ought to be a very economical method of transmitting power from the generator to the user, and it would be interesting to know if Mr. Dinwoodie had any figures or any information on that point.

Mr. Kimber

MR. H. G. KIMBER, *Associate Member*, said that the flexible pipes shown on the screen consisted of a large number of the special flexible joints mentioned by the Author. In practice one would expect such joints to develop slack and also to rust. If either of these things occurred there might be rather excessive leakage which would interfere with the transmission of power.

A figure was given in the Paper for the modulus of elasticity of water. When working at the high pressures peculiar to this system was it possible to exceed the elastic limit, and if so what happened?

Mr. Hobson

MR. J. W. HOBSON, *Member*, asked Mr. Dinwoodie if he would kindly explain what provision was made for working the plant in frosty weather.

Mr. J. C. ARTHUR, *Chairman of the Graduate Section*, asked Mr. Dinwoodie if he could give some figures as to the actual transmission efficiency of the wave transmission plant. Another point was this: Since the generator was a very high-speed pump working against a rather solid resistance, was any trouble experienced with a vibration of the generator itself? It seems probable that if any slackness developed in the connecting-rod bearings the generator would shake itself to pieces very quickly. Mr. Arthur

VOTE OF THANKS.

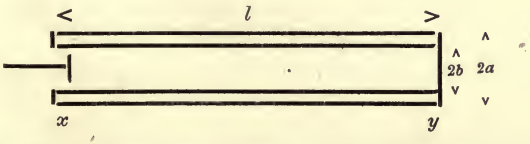
The CHAIRMAN (Mr. Harold Thomson, *Vice-President*) said they had had a most interesting Paper and, if possible, an even more interesting reply to the discussion. They were very much indebted to Mr. Dinwoodie, and he was sure he was expressing their wishes when he asked them to give him a most hearty vote of thanks. Mr. Thomson

CORRESPONDENCE.

Mr. H. G. GREEN (University College, Nottingham).

In the theory of wave transmission one of the important quantities is the expression of capacity, or the effective changes of volume for unit changes of pressure. In it there have to be considered both the contraction of the liquid itself and the expansion of the containing vessel. In the latter factor the investigation given in the Theory of Wave Transmission, p. 22 (G. Constantinesco), is not fully satisfactory as it is assumed that the mass of the walls of the tube can be concentrated on the inner surface, irrespective of the thickness, and, what is more important, that radial contractions are independent of longitudinal tensions. The quantity involved is small, but the whole term is so fundamental that initially, at any rate, it should be carefully determined. Mr. Green.

We will consider a straight cylindrical tube of length l, of internal radius b and external radius a, containing water. A pressure p above normal is subsequently applied by means of a piston.



Notation.—E Young's modulus, μ rigidity, κ volume elasticity, σ Poisson's ratio.

Case I.—The pressure of the piston on the tube itself is supported at x, *i.e.*, the tube is under a corresponding longitudinal tension.

Mr. Green

Then under the hydrostatic pressure p the internal radius is increased by

$$\delta b = \frac{b}{a^2 - b^2} \cdot \left(\frac{a^2}{2\mu} + \frac{b^2}{3\kappa}\right)p.$$

and the length by $\delta l = \dfrac{lb^2p}{3\kappa(a^2 - b^2)}$.

[See Lamb's Statics, p. 338, Ex. 4, and p. 334.]

If l^1 be the new length for the same volume enclosed

$$\text{then} \quad l^1(b + \delta b)^2 = lb^2$$

$$\text{or} \quad l - l^1 = \frac{2l\delta b}{b},$$

and we have for the movement of the piston

$$\frac{2l}{b} \cdot \frac{b}{a^2 - b^2}\left(\frac{a^2}{2\mu} + \frac{b^2}{3\kappa}\right)p + \frac{lb^2p}{3\kappa(a^2 - b^2)}$$

$$= \frac{lp}{a^2 - b^2}\left(\frac{a^2}{\mu} + \frac{b^2}{\kappa}\right).$$

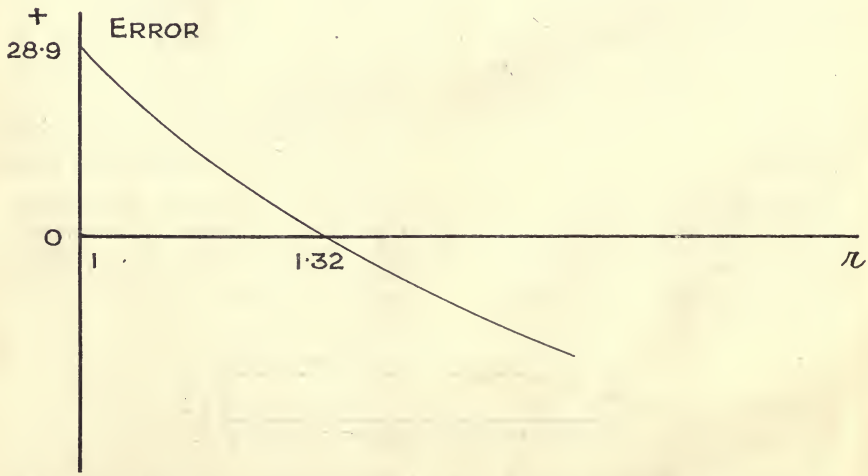
Constantinesco's method gives $\dfrac{2 \cdot 5\, lpb}{\mathrm{E}\,(a - b)}$.

The percentage error in this result is therefore

$$\left\{\frac{2{\cdot}5\ (1 + r)}{\left(\dfrac{r^2}{\mu} + \dfrac{1}{\kappa}\right)\mathrm{E}} - 1\right\} 100 = \left\{\frac{2{\cdot}5(1 + r)}{2(1+\sigma)r^2 + 3(1 - 2\sigma)} - 1\right\} 100$$

where $\quad r = \dfrac{a}{b}\,(> 1)$.

For wrought iron (·1 °/₀ C) σ = ·280 [Kaye and Laby's Tables]; the error is zero for r = 1·32 and tends to 28·9 °/₀ as r tends to 1.



In the case given (Constantinesco, *Wave Transmission*, page 4) r = 1·4 (near the critical point).

New result gives 1·598 cms.
Constantinesco's 1·511 cms.
} Supposing the pressure given as that *above* normal.

CASE II.—The piston pressure supported at y, *i.e.*, the tube not under longitudinal tension Mr. Green.

The general equations of elasticity lead to a result for the movement of the piston.

$$\frac{lp}{a^2 - b^2}\left(\frac{3a^2 + b^2}{6\mu} + \frac{2b^2}{9\kappa}\right).$$

while Constantinesco's assumptions would lead to

$$\frac{lbp}{\mathrm{E}\,(a-b)}.$$

The percentage error is

$$\left\{\frac{1 + r}{\left(\frac{3r^2 + 1}{6\mu} + \frac{2}{9\kappa}\right)\mathrm{E}} - 1\right\}100 = \left\{\frac{3\,(1 + r)}{(3r^2+1)\,(1+\sigma)+2\,(1-2\sigma)} - 1\right\}100$$

which tends to zero as r tends to 1.

Note.—In any experimental work, if the piston positions were measured relative to the free end of the pipe further allowance would have to be made of amount $\frac{2\sigma\, b^2\, pl}{(a^2-b^2)\,\mathrm{E}}$ for the longitudinal contraction of the pipe.

It is clear from the above results that the assumptions for the concentration of mass in calculating the stresses are justifiable for and only for very thin walled tubes, and that the neglect of radial effects due to longitudinal tensions leads to considerable discrepancy.

It is a matter of great importance to investigate this give of the pipe walls in the dynamical problem. The mathematical investigation, which is somewhat involved, indicates a considerable reduction in the velocity of propagation of the waves. Experiments have been made on the velocity of sound waves for water in glass tubing by Kundt and Lehmann, and by Dvorak,* which show reductions of velocity of reasonable agreement with those deduced by theory. The agreement is, however, not close enough to allow calculation to replace experiment for exact purposes and can only be used as indicating the order of the change and as a general confirmation of the theories employed. In the notation of Mr. Constantinesco we must have then the physical constants of the tube entering not only into the capacity but also into the inertia of the pipe line.

While the necessity for condensers on the line is patent the general reasons given do not seem quite satisfactory. The question is hardly so simple as that of a single reflection while the idea of an indefinitely large accumulation of energy is contradictory to one of the great points of the system—that of the supply being automatically adjusted to the demand. What really happens is that in a case of excess supply a corresponding stationary wave is established for which work done in one part of the stroke is recouped in another part.

Some experimental data of this automatic adjustment and of the

* See Barton's *Sound*, pp. 533-5.

Mr. Green

efficiencies of motors and pipe lines working at rates different from those of their design would be valuable, for although a complete installation would probably eliminate much of the extra power needed after week-end stoppages and the like, occasions must still arise when variations must be made. Knowledge also is needed of the efficiencies working with oils suitable for low temperatures before wide application can be contemplated in this country.

MR. DINWOODIE'S REPLY.

The Author

Mr. DINWOODIE thanked the meeting very much for the kind way in which they had received his Paper. It was very kind of them to listen to him as they had done, considering he had no experience of the tools and operations in which they were most interested.

Reply to the Chairman's first remarks.—The presence of air in the transmission column would have a very bad effect on the efficiency of transmission. Thus provision is made for its easy elimination. The air vessels mentioned are on the discharge side of the supply pumps, and, apart from the fact that the air is trapped in a dome, this air is not in any way in communication with the water column. Air *in the column* induces surges of high pressure, distorts the wave, and gives rise to peak pressures much in excess of those ordinarily experienced. An oscillograph record of the pressure changes in the water column with air present was shown on the screen to illustrate this point.

The only point on which men in charge of a wave-transmission installation need be informed (with regard to length) is the number of feet in the half wave-length. The total distance from tool to generator should then be arranged to be a multiple of that unit. With regard to operation it should be noted that generators should be started up and shut down with the transmission column out of communication with same; this for the reason that, with the alteration of speed the frequency reaches values at which the actual length of line becomes an odd multiple of quarter wave-lengths with the effects already described, *i.e.*, the possibility of a burst taking place.

It might be noted that the velocity of the wave in any medium, divided by the frequency, would give the wave-length. This distance would in any case be constant for any installation.

With regard to speed, if the installation is set out in accordance with the principles indicated, the generator would *resist* any tendency to alter the speed. Thus constant speed in the prime mover is desirable. The smaller the speed variation in the prime mover, the more precise must the measurement of the length of the column be. In a case where the wave-length was, say, 120 feet, and the generator was running at a speed of 40 cycles per second, there would be no tendency for speed

variation. If, however, the line were increased to 130 feet, the speed would tend to that value at which the wave-length would be 130 feet, since 4,800/130 = 37 cycles per second approximately. In that case there would be a tendency, therefore, to slow down. If carried into effect then there would be no further tendency to alteration. In using synchronous motors this point would not arise were the distances appropriate to the speed in the first place. The Author

It is necessary to calculate as indicated, the lengths of transmission column in the case of rock drills, so that these bear the stated relation to the wave-length, within limits as defined by the governing of the prime mover, if the equipment considered be that ordinarily in use at the present time for rock drilling. By the inclusion of suitable capacities rock drills or other tools may be operated independently of the distance between them and the generator. Since this point lies outside the ground covered by any experimental work known to the Author it has not been included in the Paper. It would, for reasonable treatment, demand an altogether more careful consideration of the theoretical aspects of the system.

It seems, in the Author's opinion, that rubber hose would be impossible for the efficient transmission of power by reason of the expansion which would take place.

With regard to the use of a maximum pressure of 1,600 lb. per square inch, the Author has not heard of a burst having taken place due to this maximum pressure. Solid drawn steel tubing was in use.

An extra tool may be added to the equipment at any moment provided that:—

(1) If for use simultaneously with the others, the output of the generator at full load is sufficient.

(2) If not for use simultaneously with others the power required does not exceed the generator output at full load.

Reply to Mr. Wilson.—The hammer is arrested at half displacement, so that if the particles in the pipe line had an amplitude of 23 mm. the hammer would have a displacement of half that—11½ mm. The dimensions quoted are those of the D.O.I. Generator (which was shown on the screen).

Reply to Mr. J. W. Hobson.—In *working* the plant in frosty weather no precaution need be taken, since freezing is ordinarily impossible while the water is in a state of vibration.

In the intervals between shifts, however, it would be necessary to adopt the most economical of the following plans:—

(1) Empty the pipe line at the end of operations, and recharge when next starting.

(2) Bury the main length of the transmission line, and suitably lag the remainder with non-conducting material.

The Author

(3) In certain cases, adopt a non-freezing medium. In one application of the system (C.C. gear for machine guns) a mixture of oils was used. Brine might be a possible medium.

(4) Leave the generator running light.

Reply to Mr. H. G. Kimber.—The joints mentioned were, of course, used only where necessary. The Author might have given the impression that the line was composed of joints at about 5 inch centres with 1 inch bore piping, but that was an error possibly due to the slide. At a quarry it was found most convenient, for example, to use joints at 12 feet centres (12 feet) for the main line.

In the case of slackness developing, the fact would be visible by reason of the leak, and the tightening of the retaining nut would be the cure. The removal of any one such nut exposed the packing, should this need replacement.

With regard to rusting of the joints and leakage, it would be an economy in a case of a plant of this nature to provide for the periodical inspection and greasing of the joints. The time taken would in any case be small. The joints having surfaces in contact and not a line contact would not be susceptible to leakage due to pitting, and grooving was very unlikely. Were the motion of the water of the same nature as the flow in the case of hydraulic machinery, of course, these joints would give rise to prohibitive losses. It is probable that the power is transmitted mainly through the central portion of the water, the amplitude at the periphery being very small. Again, fluids have the property of transmitting pressures equally in all directions.

With regard to the elastic limit, if the Author could have been informed as to the point at which the alteration of the volume of water under pressure gives rise to a permanent "set" or distortion, he would feel more able to go on with the reply.

Reply to Mr. J. C. Arthur.—With regard to the efficiency, an experimental method was described in which the motion of the hammer of the rock drill was recorded by a scriber caused to bear on the rim of the generator fly-wheel. From this curve the velocity of impact of hammer was deduced, and with the weight of the hammer, the number of blows per minute, and the electrical in-put to the motor, provided a means of obtaining a figure for the overall efficiency. With the type of drill then used—a much simpler hammer mechanism—figures between 80 per cent. and 85 per cent. were obtained. These results cannot, of course be universally applied. The later rock drills have not been the subject of such tests, while in general the absence of instruments analogous to the ammeter, voltmeter, and watt-meter of A.C. electricity much hamper the preparation of numerical data.

With regard to vibration, the stresses are in one direction on each connecting-rod, the minimum pressure being 100 lb. per square inch.

They are also completely balanced. A visitor to the works might check this by balancing a penny on its edge on a generator when the latter is operating a rock drill. This has frequently been done. The Author

Reply to Mr. D. Myles.—With regard to an analogy illustrating the fact that wave motion does not of itself involve flow of the medium considered as a whole, the transmission of a sound across a room, or through partitions seems the clearest. If the total distance from the tool to the generator were always a multiple of half wave-lengths, then in all cases of branch pipes the reflected waves would arrive at the generator at appropriate moments in the cycle. The only point arising is that it becomes more advisable to have such distances within a smaller limit of error, so that the speed which is normal for any one branch will be the universal speed to which all branches will tend.

With regard to the tools mentioned, the Author is not able to speak with knowledge of the plan of development which the firm (Messrs. W. H. Dorman & Co.) are following, but he thinks that it is felt that the one line of research and development, *i.e.*, the cradle-mounted rock drill, is a sufficient undertaking for an individual firm at the present time, trade conditions being as they are. As to why the rock drill was selected the Author is unable to say, but could point out that the subject is more complex than riveting, caulking and chipping hammers. The point revealed by the experimental models made is the need for making the generator of suitable design for the tools, and the power transmitted in proportion to the demand so that the vibration experienced by the operator is reduced. Vibration, due possibly to these factors, was the chief difficulty in the case of these first designs, and it has not yet been decided to proceed with this side of the question. The rock drill itself is the greatest encouragement with regard to the success of such tools.

Reply to Mr. Green.—At the present time (the Author understands), it has not been possible to bring research work on the subject of wave transmission into line with Mr. Constantinesco's mathematical analysis. In this connexion it might be said that practical work is as yet on the very fringe of the subject.

With regard to the final paragraphs of Mr. Green's remarks, the Author would emphasize the fact that the treatment of the question of condensers or capacities was far from complete. A statement to this effect is included in the text, lest the latter should be considered as anything more than an indication of the effects noted. Such considerations were reduced to the minimum necessary to introduce a description of the plant operating on the principles outlined, and of the general characteristics of such. It is hoped that it was made clear at Newcastle that in the case of varying output with a constant supply the effect was that of the combination of the corresponding stationary and progressive waves, while the alternative consideration of the two functions pressure and current, together with the introduction of a power factor (as in

The Author

alternating current electricity) was pointed out. For the given circumstances the effect might be considered as that due to the combination of a wave of power factor zero (the stationary wave of appropriate amplitude) and a second of power factor unity, the latter being responsible for the net energy transmitted. The idea of an indefinitely large accumulation of energy is certainly opposed to the Author's hope and intention which was to convey to those interested, many of whom had no previous acquaintance with the subject, the simplest possible description that could be called consistent with the effects actually to be observed.

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